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MODEL: Sediment Grain-Size Depth of Residence

PURPOSE: This technical note describes a screening-level computer model for determining the water depth at which a normally distributed sand/coarse-silt sediment becomes mobile. The mobilizing force is determined from a specified wave height, wave period, and superimposed current.

BACKGROUND: The Corps of Engineers has several tools in existence or under development that can predict the fate of sediments placed at nearshore and offshore locations (namely, STFATE (Johnson and Fong 1993), MDFATE (Moritz and Randall 1995), and LTFATE (Scheffner et al. 1995; Scheffner 1996)). However, while MDFATE and LTFATE provide high-quality predictive capabilities for the transport of dredged sediments, they require significant investments of time and resources to operate effectively. This investment of time and resources is sometimes unwarranted in the early phases of project development where quick estimates of sediment motion are all that is desired. The numerical model described herein provides a simple tool for determining the limiting depth at which incipient motion of a particular-sized sand particle occurs for a given set of hydrodynamic conditions. Using this tool that provides the threshold depth for motion, one can quickly determine that water depths much deeper than the threshold will provide a stable environment for the sediment, while water depths much more shallow will result in active motion of the sediment. This tool, therefore, allows quick screening of the suitability of potential locations for dredged-material placement.

The input data requirements of the model are wave height, wave period, tidal current, and the median grain size value, D_{50}. During the planning phase of a dredging project, the median grain-size value of the in situ dredged material is either known or is estimated. The hydrodynamic conditions for a coastal location can be estimated from the Corps of Engineers wave hindcast and tidal current databases. These databases can be found on the U.S. Army Engineer Waterways Experiment Station URL Internet site *http://bigfoot.wes.army.mil/cetn.index.html*. Therefore, all of the required input data for the model can be readily obtained. In any particular case, the sensitivity of the result to particular hydrodynamic or grain-size values can be obtained by methodically varying the parameters.

Several important simplifying assumptions were made in the development of this model of which the user should be aware. These are outlined in detail below along with a description of the procedures used within the model to translate wave and current data into bed shear stresses and the determination of incipient sediment motion.

THEORY: Most noncohesive (sand/coarse-silt) transport models have been developed for current-only environments. The near-bottom current outside the boundary layer, coupled with the bed roughness, is used to calculate a near-bottom shear stress. There is a critical stress value at which a given grain size will begin to move as bed load. In the present application, waves often produce

the dominant force at the sediment-water interface. Therefore the current-only theories must be modified to include the effects of waves. A method developed by Bijker (1971) is used in this model to incorporate the effects of waves on the incipient motion of sediments. This modification is a factor by which the current velocity is multiplied to account for the effects of waves (Swart 1976). The wave effects are included by increasing the current velocity to a value that would be equivalent to the combined current/wave effects. The methodology used here is the same as that used in LTFATE (Scheffner et al. 1995). This effective increase in velocity for currents accompanied by waves V_{wc} is written as a function of the current velocity V_c in the absence of waves as follows:

$$V_{wc} = V_c \left[1.0 + \frac{1}{2} \left(\xi \frac{\hat{u}_0}{V_c} \right)^2 \right]^{1/2} \tag{1}$$

where

$$\xi = \hat{C} \left(\frac{f_w}{2g} \right)^{1/2} \tag{2}$$

$$\hat{C} = 18 \log \left(\frac{12d}{r} \right) \tag{3}$$

$$f_w = \exp \left[-5.977 + 5.213 \left(\frac{r}{a_0} \right)^{0.194} \right] \tag{4}$$

$(\text{if } f_w > 0.3, f_w = 0.3)$

$$\hat{u}_0 = \frac{Hgk}{2\sigma} \frac{1}{\cosh(kd)} = \frac{HgkT}{4\pi} \frac{1}{\cosh(kd)} \tag{5}$$

$$a_0 = \frac{Hgk}{2\sigma^2} \frac{1}{\cosh(kd)} = \frac{H}{2} \frac{1}{\sinh(kd)} \tag{6}$$

where $\hat{u}_0$ is the amplitude of the orbital velocity at the bed (Van De Graff and Van Overeem 1979), computed according to linear wave theory (Ippen 1966, 28), and a_0 is defined as the orbital excursion (amplitude) at the bed (Swart 1976), computed from linear wave theory (Ippen 1966, 29). In the above, the parameter f_w is defined as the bottom friction coefficient (Jonsson 1966). The parameter r is the hydraulic bed roughness and taken to be 0.197 ft (0.06 m) (Van De Graff and Van Overeem 1979). The terms H, k, σ, and T represent wave height (ft), wave number (ft^{-1}), angular frequency (sec^{-1}), and period (sec), respectively. The terms d and g represent water depth (ft) and acceleration of gravity (ft sec^{-2}), respectively.

A method developed by Ackers and White (1973) is used to determine the water depth for initiation of motion for a specified grain size, current condition, and wave condition. The original Ackers and White relationships predict sediment transport and initiation of sediment transport as a function of sediment grain size, depth, and depth-averaged current velocity. As stated previously, this method was designed for current-only environments, and the above described effective velocity that accounts for waves and currents will be substituted for the current velocity in all equations. The equations were not developed for a single grain size, but rather for uniformly graded noncohesive sediment with a median grain diameter in the range of 0.04 mm to 4.0 mm, assuming only a small fraction (<5-17 percent depending on mineralogy) cohesive clays and fine silts (White 1972). Many equations have been developed to describe noncohesive sediment transport, and the various methods have been compared with multiple data sets (Brownlie 1981). These comparisons indicate that the Ackers and White method performs as well or better than the other well-recognized procedures.

The Ackers-White transport equations relate initiation of sediment transport to two dimensionless quantities. The first, a nondimensional grain size D_{gr}, is defined as a function of the ratio of the immersed particle weight to the viscous forces acting on the grain:

$$D_{gr} = D\left[\frac{g(s-1)}{\upsilon^2}\right]^{1/3} \tag{7}$$

where

D = sediment diameter (i.e., D_{50}), ft

g = acceleration of gravity, ft/sec^2

s = sediment-specific gravity

υ = fluid kinematic viscosity, ft^2/sec

The value of D_{gr} is used to categorize the sediment as coarse or transitional, with the following coefficients defined for the two sediment classifications:

a. Coarse sediments: $D_{gr} > 60$.
$n = 0.0$
$A = 0.17$

b. Transition sediments: $1.0 < D_{gr} \leq 60.0$.

$$n = 1.00 - 0.56 \log\left(D_{gr}\right) \tag{8}$$

$$A = \frac{0.23}{\sqrt{D_{gr}}} + 0.14 \tag{9}$$

The second nondimensional parameter F_{gr} represents particle mobility defined as the ratio of shear forces to the immersed sediment weight:

$$F_{gr} = \frac{\upsilon_*^n}{\sqrt{gD(s-1)}}\left[\frac{V_{wc}}{\sqrt{32}\log\left(10\frac{d}{D}\right)}\right]^{1-n} \tag{10}$$

where d is the mean depth of flow (ft), and υ_* is the shear velocity (ft/sec), which can be defined from Chow (1959, 204) as:

$$\upsilon_* = \frac{\sqrt{g}V_{wc}}{C_z} \tag{11}$$

where C_z is the Chezy coefficient defined by

$$C_z = \left[\frac{\left(1.48d^{0.167}\right)}{mann}\right] \tag{12}$$

and *mann* is the Mannings $N = 0.025$. Initiation of motion of sediments can then be estimated from the following value:

$$\frac{F_{gr}}{A} - 1 \tag{13}$$

If this value is less than or equal to zero, there is no movement of a uniformly graded sediment with the specified median grain size. If the value is above zero, then there will be sediment movement. The rate of transport can also be determined by further analysis of the parameters (see Scheffner et al. 1995). If the value of Equation 13 is only slightly above zero, transport will be minimal and essentially zero. Therefore, under these conditions, transport and total erosion will be barely noticeable.

Application of the above methods to determine initiation of motion is determined by the user first specifying wave height, wave period, current velocity, and median grain size. The program then estimates the water depth at which these wave conditions will begin breaking, i.e., the water depth at which the above methods are valid. Each water depth between the breaking value and 250 ft is analyzed at 1-ft increments until the value of Equation 13 is negative (no transport). If the sediment does not move at the location of breaking, or the sediment is still mobile at 250 ft water depth, the program will indicate to the user that the depth of residence cannot be calculated and will provide the reason.

EXAMPLE APPLICATION: A sample application of the grain-size depth of residence screening model is given below. In this example, the driving force for sediment motion is a current of 0.2 m/sec (0.66 fps) combined with a wave that is 3 m (10 ft) high with a 10-sec period. The sediment is identified by a median grain size (D_{50}) of 0.2 mm (0.0079 in.). The program input and output is provided below where program text (requests for information) is given in *italics* and user-provided answers are given in **bold.**

Program to determine depth of residence
Input wave height , wave period, current
velocity and median grain size. Program
determines depth at which sediments will
remain stationary at these conditions.

Note: Input values must be greater than 0

Do you want to input in
metric (1) or English (2) units?
>1

Input wave height (m)
>3

Input wave period (s)
>10

Input current velocity (m/s)
>0.2

Input D_{50} grain size (m)
>0.0002

FOR THE FOLLOWING CONDITIONS:
wave height = 3.00000 (m)
wave period = 10.0000 (s)
current velocity = 0.200000 (m/s)
grain size = 0.200000E-03 (m)
SEDIMENT WILL NOT MOVE AT A
DEPTH OF 26.5176 m or greater

As the example shows, the program determined that for the given hydrodynamic conditions, the given sediment will be stable at water depths greater than 26.5 m (87 ft). Hence, if this screening tool was being used to determine the depth at which sediments for a dredged-material capping project would be stable, then as an initial estimate one could say that depths would have to be greater than 26.5 m (87 ft). Conversely, if the desire was to have the sediment move under the given conditions, then as an initial estimate one could say that the depth would have to be less than 26.5 m (87 ft). The results should be considered a rough estimate. If the actual depth at which the sediment was to be placed was nearly 26.5 m (87 ft), then a more thorough evaluation of the site would be required. If the actual placement site was much deeper or much more shallow than 26.5 m (87 ft), one could

assume with some confidence that the sediment would be stable or mobile, respectively. The obvious advantage of this grain-size depth of residence tool is that it can be applied quickly and easily to estimate the depth of motion of sediments for given hydrodynamic conditions.

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> Gailani, J., Davis, J., and Pollock, C. (1999). "MODEL: Sediment grain-size depth of residence," *DOER Technical Notes Collection* (TN DOER-N4), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

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